FISH MUCUS: *IN SITU* MEASUREMENTS OF POLYMER DRAG REDUCTION

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ABSTRACT

The external layer of mucus on fish was investigated as a drag reducing polymer. Comparing velocity profiles for water flow over rainbow trout (*Salmo gairdneri*) and wax models of trout with and without hydrodynamically smooth surfaces revealed that the integumental mucous secretion can significantly reduce the rate of momentum transfer through the boundary layer. The difference in momentum transfer is expressed as a reduction in friction drag and discussed in view of the overall drag experienced by fish.

INTRODUCTION

Virtually all fishes are covered with an integumental mucous secretion that is involved in many aspects of their biology, ranging from disease resistance and rearing of young to shelter and locomotion (Jakowska, 1963; Winn, 1955). In locomotion, the layer of mucus is assumed to reduce friction drag. Dissolved in water, these external secretions have been shown to reduce friction drag in turbulent pipe flow (Hoyt, 1975; Ling and Ling, 1974; Rosen and Cornford, 1971) and pulsed laminar flow (Driels and Ayyash, 1976). These results have been attributed to the "Toms effect" (after Toms, 1948), in which dilute solutions of high-molecular-weight polymers flowing in tubes yield friction-drag coefficients less than values predicted for Newtonian fluids. Most authors agree that fish mucus reduces drag. No one, however, has estimated the degree to which mucus can decrease the friction drag experienced by swimming fish.

The drag-reducing ability of fish mucus in solution has been determined by a turbulent flow rheometer (Hoyt, 1965, 1975; Rosen and Cornford, 1971). In addition, Ling and Ling (1974) investigated the velocity field in the laminar sublayer of mucus injected into water flowing in a tube. In all these experiments, mucus samples were removed from fish and analyzed for drag reduction as a function of mucus concentration. In reality, mucus is secreted by the integument and diffuses into water at some unknown rate. The concentration gradients are unknown. Hence, the drag reduction is also unknown.

In the present paper, the drag-reducing ability of mucus is investigated by comparing velocity profiles of the flow over the surface of freshly killed fish to those over wax models with and without smooth surfaces. Direct measurements of the velocity profiles provide estimates of the rates at which momentum is transferred from the free-stream flow (a region in which the effects of a boundary are trivial) to the surface of the fish or wax models. These profiles are used, in turn, to determine

the reduction in friction drag resulting from mucus in the boundary layer (a region of flow between the free-stream and the surface of the fish, where the effects of viscosity are quite strong).

Methods

Density and viscosity measurements

Mucus of healthy rainbow trout (*Salmo gairdneri*, Richardson) was removed by rubbing the fish from head to tail with sterile gloved hands. The mucus was transferred from the tail to a sterile petri dish and used within 1 h. Its density was measured over a temperature range of 10–31 °C by standard pycnometric technique using a 2.0-ml pycnometer.

A Ferranti-Shirley cone and plate viscometer was used to measure mucus viscosity in shear rates less than $8000 \, s^{-1}$. Mucus samples for viscometry were collected as above.

Flow visualization

Use of an open-circuit flow tank avoided the possibility of recycling polymers shed by the fish (Fig. 1). Flow through the 14.0-cm-diameter test chamber was controlled by a downstream tube of flexible polyethylene equipped with a C-clamp.

A 35-mm camera and a Strobotac stroboscope were placed on opposite sides of the test chamber. A 50-mm lens with extension tubes provided a shallow depth of field and a 1.7-fold magnification on the film.

Two wax models were made from a plaster cast of a 19.0-cm-long trout. One was coated with silicone lubricant (stopcock grease) to simulate the hydrodynamic smoothness of a layer of mucus. The other model was left untreated, retaining the surface features of the scales.

Fish 19–20 cm long were killed by a sharp blow to the skull and placed on a platform in the test chamber with their lateral sides up and dorsal sides facing the camera. The camera was focused on a portion of the lateral side of the fish 8 cm
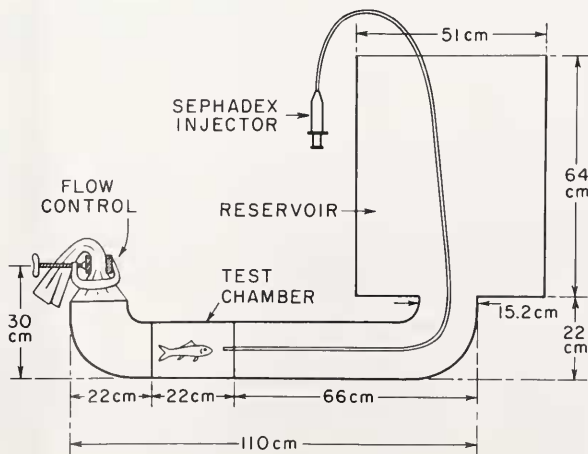

FIGURE 1. Schematic diagram of the flow system used in the study. The reservoir capacity is 120 l. The test chamber is a Plexiglas tube with an inside diameter of 14 cm. The Sephadex injector consists of a 60 cm³ syringe and 200 cm of 0.2 cm diameter Tygon tubing.

from the snout. The flow tank exit was then opened and G-25 coarse-grained Sephadex particles (100–300 μm diameter) were injected 2–4 cm in front of the fish. Photographs were taken at a shutter speed of 0.25 s with a stroboscope frequency of 32 flashes/s, giving eight images of each particle on a single frame. The procedure was repeated for the wax models with and without silicone lubricant.

Velocity profiles

The distances that Sephadex particles traveled between strobe flashes and their heights above the surface of the fish were measured to within 40 μm with a caliper and a microscope, from negatives. Two intersecting line segments were fitted to the data by a least-squares linear regression (Hudson, 1966). Thus, each resulting velocity profile consisted of two lines: an upper line corresponding to the free-stream velocity and a lower segment corresponding to the boundary layer flow. The lower segment was operationally defined as the velocity gradient in the boundary layer ($\partial v_x / \partial y$, where v_x is fluid velocity in cm/s, and y is cm height above the fish's surface). Thus, a series of such profiles could be used to obtain data for the boundary layer velocity gradient as a function of free-stream velocity. This gradient, in turn, was used to describe momentum transfer and friction drag on the fish and wax models.

RESULTS

Density and viscosity measurements

In no case did the density of mucus differ from that of water by more than 1%. Cone and plate viscosimetry indicated that the viscosity of mucus was about the same as water; that is, about 1 centipoise. However, the viscosity of a polymeric solution such as mucus is sensitive to degradation of high-molecular-weight fractions (White and Hemmings, 1976). I have no estimate of the degree of degradation that might have occurred between the time the samples were collected and tested.

Velocity profiles

Velocity profiles over the surface of a mucus-covered fish are shown in Figure 2, with intersecting line segments fitted to the data for two free-stream velocities. As the free-stream velocity increased, the velocity gradient also increased. The velocity gradients were 2.6 s^{-1} for the low flow rate and 7.2 s^{-1} for the high flow rate.

Figure 3 compares the boundary-layer velocity profile over the surface of a fish to that over the smooth wax model. The velocity gradient for the fish was approximately 40% lower. Since the rate of momentum transfer from the free-stream flow to the surface of the fish is proportional to the velocity gradient, the results summarized in Figure 3 suggest that mucus on the surface of the fish decreased momentum transfer and, ultimately, friction drag.

Double-segment regressions like those in Figure 2 were used to determine the degree to which mucus reduced the rate of momentum transfer to the surface of the fish. The slope of the lower segment represents the average velocity gradient within the boundary layer. This slope was used to approximate the shear stress acting on the surface of the fish and models using Newton's law of viscosity.

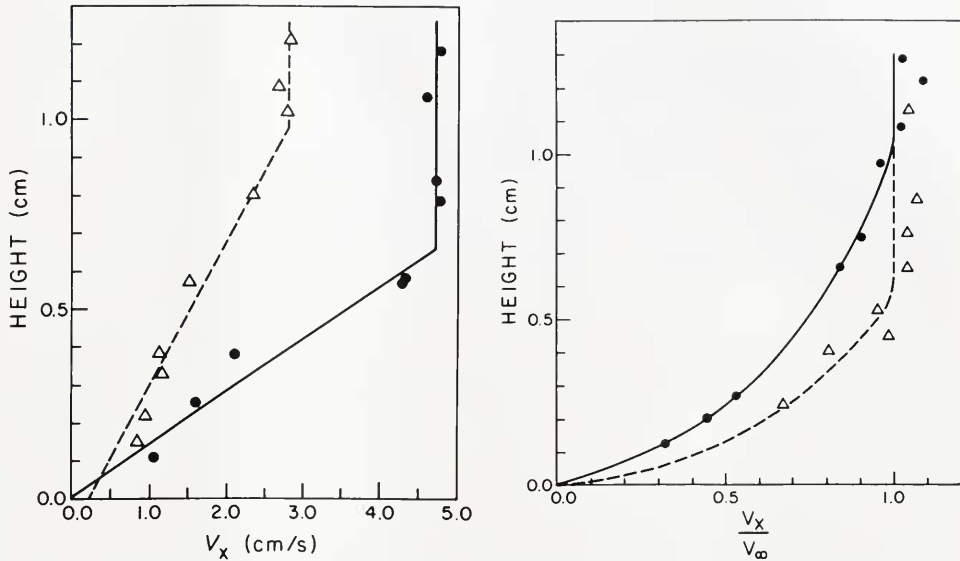$$\tau_0 = -\mu \frac{\partial v_x}{\partial y}$$

FIGURE 2. Height above the surface of the fish plotted against velocity (v_x) to give a velocity profile. Solid circles and triangles correspond to a free-stream velocity of 4.7 and 2.8 cm/s respectively. The slanted portion of the curves represents the velocity gradient in the boundary layer. The regression for the left segment of the solid line is $v_x = 0.05 + 7.17$ (height) ($r^2 = 0.932$, $N = 5$) and for the broken line is $v_x = 0.24 + 2.6$ (height) ($r^2 = 0.955$, $N = 6$).

FIGURE 3. Height above the surface is plotted against normalized velocity (v_x/v) for the fish (solid circles) and wax model with silicone lubricant (triangles). The free-stream velocities about the fish and model are, respectively, 2.15 and 2.19 cm/s.

where τ_0 is the shear stress at the surface of the fish, μ is the dynamic viscosity of water, and v_x is the local velocity of water at any height (y) above the surface.

The local friction factor was defined as the ratio of wall shear stress to kinetic energy per unit volume of fluid in the free stream by the following relationship (DeNevers, 1970):

$$f_x = \tau_0 (\tfrac{1}{2}\rho v_\infty^2)^{-1}$$

where f_x is the local friction factor, ρ is the density of water and v_∞ is the free-stream velocity.

In Figure 4, the local friction factor is plotted against the local Reynolds number for a variety of flows over the fish and wax models. The log of the local friction factor versus the log of the local Reynolds number was fitted by least-squares linear regression. The regression lines for the wax models with and without a smooth surface were not significantly different. The regression line for the fish was significantly lower than those from the wax models (F test, $P < 0.025$). The slope of the line for friction-factor versus Reynolds number was more negative for the fish, although not significantly different from the wax models. The solid line in Figure 4 is the predicted local friction factor for flow over a flat plate in laminar flow (DeNevers, 1970). The local friction factor for the wax models approximates the local friction factor for a flat plate at the same Reynolds number. This is in accordance with expected results for a streamlined body (Goldstein, 1965).
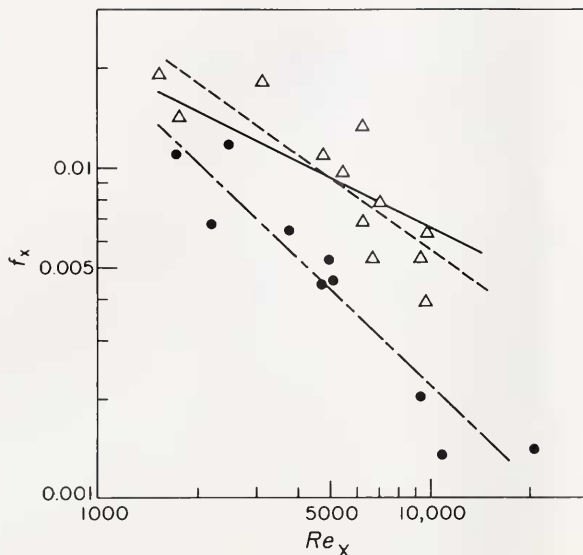
FIGURE 4.   Local friction factor (f_x) is plotted against the local Reynolds number (Re_x) for the fish (solid circles) and both wax models (triangles). The solid line corresponds to the predicted friction factor for flow over a flat plate in laminar flow. The broken lines represent the regression equations which for the fish is $f_x = 14.45\ Re_x^{-0.95}$ ($r^2 = 0.88$, $N = 11$) and for the wax models is $f_x = 4.69\ Re_x^{-0.73}$ ($r^2 = 0.70$, $N = 12$). The slopes of these lines are not significantly different.

DISCUSSION

The velocity gradient about an object moving through a fluid can be considered a measure of the transfer of momentum from fluid in the free-stream to the surface of the object, by the action of viscosity: the greater the velocity gradient, the greater the rate of momentum transfer. The velocity gradient can be modified by changes in surface texture (Goldstein, 1965) and, as this study has shown, by mucus in the boundary layer. The velocity gradient about a fish is less steep than that about a hydrodynamically smooth model of the animal. This difference reduces the local friction factor on the order of 50%, with a trend towards a greater reduction at higher Reynolds numbers. The reduction in frictional drag may reasonably be attributed to mucus. The possibility that mucus on fish is behaving as a "Toms effect" solution should be considered. In this case, high molecular weight polymers from the mucus may be decreasing the rate of momentum transfer from the fluid to the animal's surface.

Several conditions must be satisfied for mucus to act as a drag reducer and for my treatment of velocity gradients to be valid: (1) Mucus must consist, in part, of polymers soluble in water and with molecular weights exceeding 50,000 (White and Hemmings, 1976). (2) There must be turbulent or pulsed laminar flow about the fish (Driels and Ayyash, 1976). And (3) the density and viscosity of the fluid from the surface of the fish outwards must be constant.

Existence of the first condition is supported by studies of mucus/water solutions subjected to turbulent flow in pipes (Hoyt, 1975; Rosen and Cornford, 1971). Regarding condition (2), however, I am not aware of any analyses of the size distribution of polymers in fish mucus. The velocity profiles presented here indicate that the flow about the fish and wax models is turbulent, supporting the second

condition. Although the local Reynolds number for flow over the fish does not indicate turbulence, the Reynolds number for flow in the tank exceeded 2000 in all situations, indicating a turbulent flow regimen was imposed on the fish and wax models. Swimming fish most likely experience turbulent flow or, with body undulations, pulsed laminar flow. Lastly, constant density and viscosity within the boundary layer is supported by the present measurements.

This study shows that mucus decreases the friction drag experienced by fish. The total drag on a swimming fish consists of pressure drag as well as friction drag. Webb (1978) estimated total drag coefficients of swimming fish, using measured power outputs. The relative importance of friction drag to total drag, however, remains unknown. Estimates of total drag using rigid models or dead fish (*e.g.* Gero, 1952) are difficult to apply to a moving animal due to the problems of (1) analyzing the pressure field about an undulating body (Wu, 1977), (2) the unknown nature of mucus, or lack thereof, on a dead fish or rigid model, and (3) the unknown flexibility of models or fish. While the present study suggests that the rainbow trout has a mechanism by which it decreases friction drag, such a reduction may not decrease total drag. The contribution of friction drag to total drag is, at present, unknown, and may be a small portion of total drag. Wu (1977), however, suggests that for a streamlined body such as a fish, the majority of drag is frictional. Lastly, there is evidence that polymer additives can delay the point of wake separation, reducing the size of the wake and the pressure drag; and that this effect can be seen in laminar flows (White and Hemmings, 1976).

Polymer drag reduction is by no means limited to teleosts, and may not be limited to the individual producing mucus. Breder (1976) suggests that schooling fish may take advantage of polymer drag reduction. He observed that fish at the trailing end of a school beat their tails less often than did fish at the leading edge, indicating a reduction in drag arising from dissolved polymers from the leading fish. Mucus secretion and its role in drag reduction can be found in a variety of biological situations. Hoyt (1970, 1974) has shown that mucus from marine organisms such as algae and bacteria can reduce drag. Moreover, many marine animals, such as cephalopods, coelenterates, and sponges, have mucus on their surfaces. The study of forms where separate components of drag can be determined would provide much insight into the role of mucus in drag reduction.

ACKNOWLEDGMENTS

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